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HIGH ALTITUDE TURBULENCE FOR SUPERSONIC CRUISE VEHICLES

L. J. Ehernberger*

The characteristics of high altitude turbulence and its associated meteorological features are reviewed. Findings based on data from NASA flight research programs with prototype military aircraft, the XB-70 and YF-12A, are emphasized. An example of detailed numerical atmospheric simulations, which may provide greatly increased understanding of these earlier turbulence observations, is presented. Comparisons between observation and numerical simulation should help to delineate the limitations of present theoretical analysis and observation techniques and to ultimately improve our understanding of atmospheric processes in the stratosphere.

INTRODUCTION

Supersonic cruise aircraft (SCA) have been designed and operated for military missions (SR-71) and civilian passenger transportation (Concorde). Their optimum cruise altitudes are 5 to 10 km above the flight levels used by subsonic passenger transport aircraft. In terms of the atmospheric temperature structure these supersonic cruise altitudes are in the lower stratosphere where temperature is nominally constant or increases slightly with altitude. However, in the tropics the base of the stratosphere, or tropopause altitude where the minimum temperature occurs, may be near or even above SCA flight altitudes. In terms of atmospheric wind structure supersonic cruise altitudes are typically above the jet stream core or the level of maximum windspeed and commonly experience decreasing windspeed as altitude increases. In winter the wind profile is typified by a speed minimum near or somewhat above SCA cruise altitudes and stronger westerly winds higher in the stratosphere. During the spring a reversal of the westerly winds occurs in the upper stratosphere and propagates easterly winds downward to the SCA cruise altitude region. Thus these higher cruise altitudes present SCA with somewhat

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different atmospheric features than typically experienced by subsonic passenger aircraft at flight levels closer to, or below, the tropopause and the tropospheric jet stream. In addition, differences in SCA structural and propulsion system response to gusts add concern. Consequently, the onset of supersonic cruise aircraft operation in the 1960s was attended by increased interest in the higher altitude turbulence environment.

The purpose of this paper is to review the characteristics of high altitude turbulence (Refs. 1-4) and its associated meteorological features (Refs. 5-7). Findings based on data from NASA flight research programs with prototype military aircraft, the XB-70 and YF-12A, are emphasized. An example is presented of small-scale numerical atmospheric gravity wave simulation capability, which may provide greatly increased understanding of these earlier turbulence observations. Comparisons between observation and numerical simulation would contribute to the evaluation of the numerical techniques and delineate some of the limitations of analytical theory. Results of such comparisons would enable better application of simulation and theory to describe the physical mechanisms by which atmospheric wind and temperature structures lead to turbulence in the lower stratosphere and, perhaps more importantly, at even greater altitudes where aircraft sampling has not yet been possible.

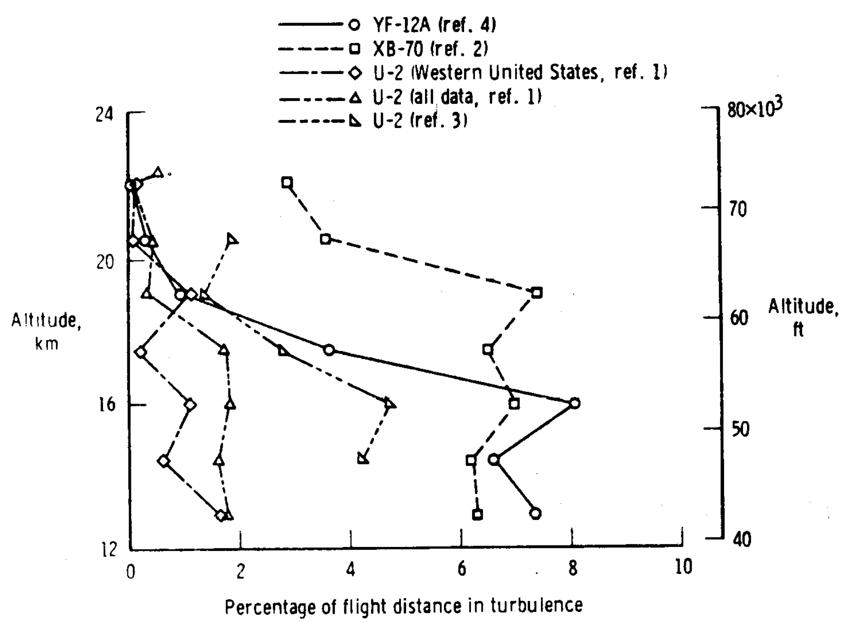


Fig. 1 Amount of Turbulence Versus Altitude

TURBULENCE CHARACTERISTICS

Atmospheric turbulence has been a constant companion of aviation history. At lower altitudes rough air generated by wind, thermal convection, and clouds is frequently experienced during flight. The relative portion of total flight distance over which turbulence is experienced generally decreases with altitude, reaches a minimum at middle tropospheric altitudes, and then increases again as flight altitudes approach the jet stream layer and tropopause where it reaches a maximum. At the higher altitudes used by SCA in the lower stratosphere the amount of turbulence experienced has usually been found to decrease notably at altitudes near 20 km (Fig. 1). The distribution with altitude found in different sampling programs is somewhat dependent on the aircraft threshold criteria used, the geographical region, and seasonal influences (Ref. 4). A vivid depiction of the ride quality improvement available at higher altitudes during much of the year is given by the YF-12A airplane cumulative frequency distributions for the peak normal accelerations due to turbulent gusts (Fig. 2).

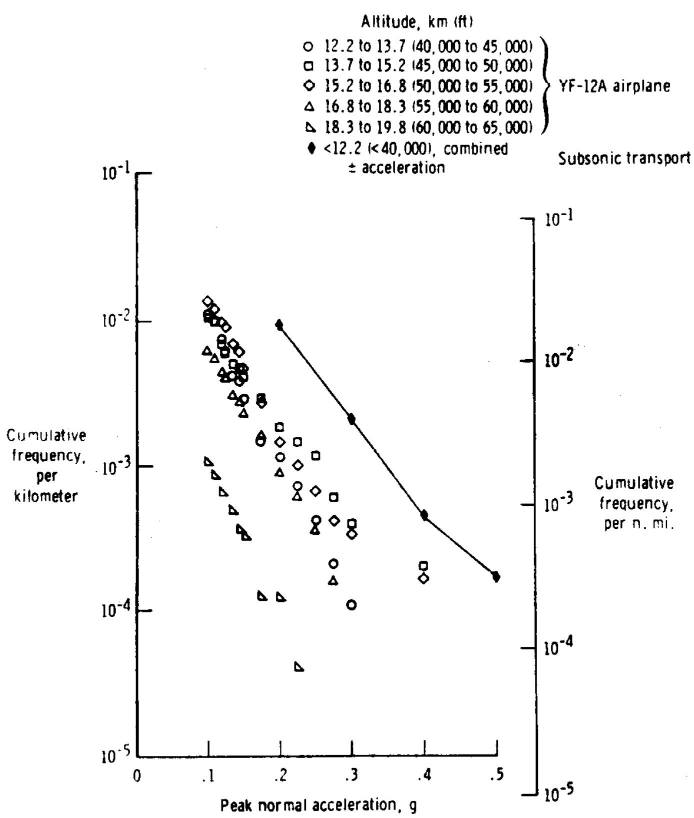


Fig. 2 Comparison of Cumulative Frequency Distributions of Peak Accelerations due to Turbulence

These data show that the rate of encountering specified gust acceleration amplitudes at altitudes near 19 km is an order of magnitude less than at lower altitudes closer to the tropopause and jet stream.

Turbulence at supersonic cruise altitudes has often been said to be "more patchy" than in the upper troposphere. This is not surprising, because of the lower wind speeds and greater static stability of the nearly isothermal temperature profile in the lower stratosphere. The YF-12A data (Figs. 3 and 4) exhibit a median patch length of less than 10 km and a median patch thickness of less than 0.5 km. For patches of moderate or greater intensity, the average patch dimensions were approximately 24 km in length and 0.7 km in thickness. As described in reference 4, the YF-12A turbulence patch length distributions were obtained from data at flight path angles shallower than 2 degrees, and the thickness distributions were obtained from data at flight path angles steeper than 3 degrees. In some cases patches were encountered at multiple altitudes throughout a region several kilometers deep. In other cases the turbulence was restricted to a narrow region or individual layer. These observations imply that the atmospheric motions that generate or trigger individual patches of turbulence are correspondingly shallow and of limited horizontal extent.

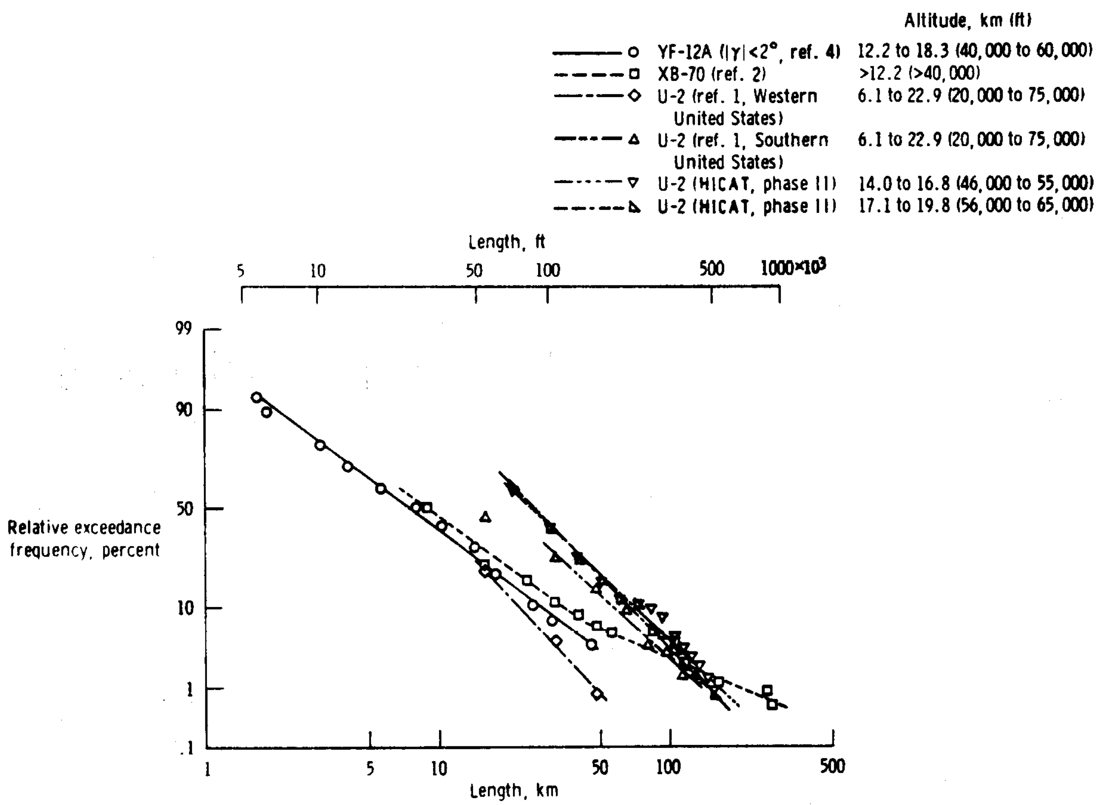


Fig. 3 Comparison of Turbulence Patch Length Distributions From Various Sources

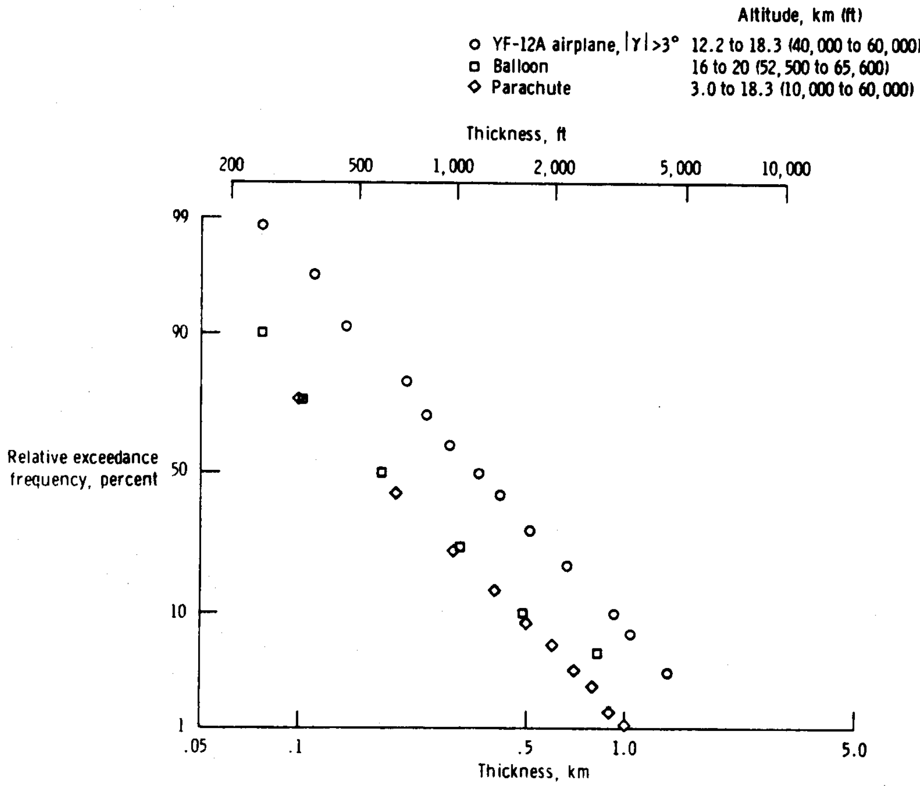
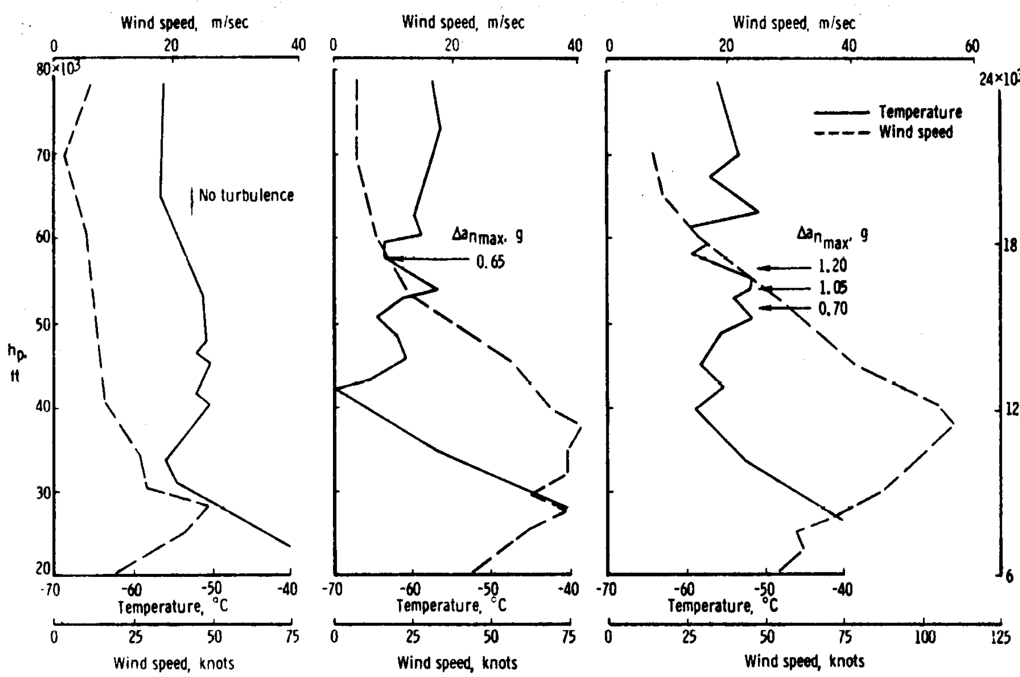


Fig. 4 Turbulence Patch Thickness Distributions From Three Sources

METEOROLOGICAL CHARACTERISTICS

Most high altitude turbulence encounters are associated with high wind speeds near the tropopause, and many also include lower altitude forcing features such as weather fronts, convective cloud development, or obvious mountain wave activity. With weak flow throughout the tropopause and lower stratosphere, smooth conditions occur at SCA cruise altitudes. Smooth high altitude conditions also occur at times when there is weak flow at high altitudes above strong flow near the tropopause. Example wind and temperature profiles are illustrated for smooth flight conditions in Fig. 5(a) and for turbulence encounters in Figs. 5(b) and 5(c) at flight levels which are 5 to 10 km above the tropopause and maximum wind speed altitude. These profiles show that the rawinsonde-measured wind structure is relatively smooth, while the rawinsonde temperature measurements provide more detailed vertical resolution. In view of the 12-hr time separation and horizontal distances between upper air observations on the order of hundreds of kilometers, the rawinsonde wind resolution is appropriate for most meteorological applications. However, the wind resolution is too coarse to accurately measure the vertical



(a) No turbulence.

(b) Turbulence during constant-altitude cruise.

(c) Turbulence during climb.

Fig. 5 Example Wind and Temperature Profiles for Various Turbulence Conditions (observed gust accelerations are noted at their respective flight altitudes)

wind shear across individual turbulence layers. In contrast, the higher resolution temperature measurements do show details on the scale of typical patch thicknesses, but the time and space between observations are too great to show a desirable degree of continuity from one temperature profile sounding to another in the majority of cases. In spite of these atmospheric observation deficiencies several useful forecasting procedures have been developed for high altitude turbulence.

Particular features that have proven valuable in predicting the presence of high altitude turbulence include windspeeds at the level of maximum wind and at the 100-mb pressure level (nominally 16-km altitude), strong vector wind shears in the lower atmosphere and near the flight altitude, and both enhanced temperature lapse and enhanced inversion rates near the flight altitude (Ref. 5). These features were evaluated for high altitude turbulence encounters using the nearest available upper-air data. The separations between upper-air observations and turbulence encounters were on the order of 4 hr and 200 n.mi. but did vary widely. Specified values of threshold criteria for these features are listed in Table 1 along with the percentage of turbulence observations in each intensity category for which the individual variables are within their specified range. For example, only 4 percent of the smooth cases had 100-mb

Table 1

PERCENT OF SAMPLES MEETING THE SPECIFIED VALUES OF THE METEOROLOGICAL PARAMETERS FOR TURBULENCE INTENSITY CATEGORIES AND CLIMATOLOGY

Parameter	Specified value	Percent of turbulence cases: smooth	light	moderate	Annual percent
Maximum wind	$\geq$70 knots (36 m/sec)	36	37	69	25
100 mb wind	$\geq$40 knots (21 m/sec)	4	7	56	20
Low-altitude shear	$\geq 0.020\ sec^{-1}$	16	9	56	10
Flight-altitude shear	$\geq 0.005\ sec^{-1}$	16	48	69	47
Flight-altitude lapse	$\geq$4.0°C/km	12	26	56	36
Flight-altitude inversion	$\geq$5.0°C/km	32	18	56	32

windspeeds of 40 knots or greater, and similarly, 56 percent of the moderate cases had low altitude wind shear of 0.020 per sec, or more. The final column on the right-hand side of Table 1 gives the climatological frequency for the specified range of each variable on an annual basis (Ref. 7). Forecasts for moderate or stronger turbulence intensity (based on having three or more of the variables above the specified values for their specified ranges) were 63 percent correct. Forecasts for less than moderate intensity were 92 percent correct.

Techniques for predicting stratospheric turbulence were extended from the features observed on individual rawinsonde profiles to a large number of time-rate-of-change variables and derived parameters that could be evaluated on the bases of upper-air forecasts and observed data. In Ref. 8 it was shown that the combined resulting techniques could forecast areas of clear air turbulence to an accuracy of 70 to 80 percent. This work also reaffirmed the dependence of some cases of high altitude turbulence on mountain wave activity at lower altitudes (Refs. 9 and 10). Mountain waves result from the force of gravity acting on atmospheric stability (that is, on the buoyancy of air parcels displaced vertically) to generate oscillatory wave behavior as air flows over mountain ridges. In one sampling, 13 of 17 high altitude turbulence cases either were above an area where the 700-mb wind component perpendicular to a mountain ridge line was 10 m/sec or greater, or were above a closed low pressure region. Another mountain-wave-related feature examined was the curvature of the wind profile (the second derivative of the windspeed with respect to altitude divided by the windspeed). This was done to examine the role of the wind profile curvature in the troposphere on the upward propagation of mountain wave motion. According to theory, the mountain wave amplitude depends on the vertical structure of the so-called Scorer parameter. If the Scorer parameter decreases with altitude, the wave mode amplitudes will increase until they reach their level of trapping or reflection. Sufficiently long wavelength components may experience amplification but not trapping. The Scorer parameter is reduced by decreasing static stability, increasing windspeed, and increasing wind shear. For the curvature evaluation, the wind shear was taken over altitude intervals of 1.5 km and inspected for an increase with altitude between the 700-mb level and the middle troposphere. A curvature increase was present in 40 of 47 high altitude turbulent areas but in only 1 of 43 nonturbulent areas sampled (ref. 10). Thus both qualitative weather observations and statistics based on measured data support a strong relationship between high altitude turbulence and mountain wave activity that can be incorporated in SCA cruise altitude turbulence forecasting procedures.

Even though these results may satisfy the meteorologist as a forecaster they also stimulate the meteorologist as an atmospheric scientist. Rotor and lenticular clouds, large surface pressure gradients across mountain ridge lines, and updrafts and downdrafts frequently provide observable indications of strong mountain wave activity in the lower troposphere for the meteorologist and the pilot. In many cases the atmospheric structure may cause a large portion of the wave energy to be reflected downward or trapped at lower altitudes. However, in some cases part of the wave energy is not trapped at lower altitudes but does propagate upward through the tropopause and into the stratosphere where it is often not attended by readily observable features. In addition, as the wave energy propagates into the stratosphere it meets layers with greatly different values of natural atmospheric periods and wavelengths because of the drastic changes in temperature lapse rate (stability) and windspeed. The force of gravity can act on layers of differing atmospheric stability stratification at any altitude to generate gravity wave activity, which may become unstable (Kelvin-Helmholtz instability). To the meteorologist as an experienced observer, the many combinations of stability and wind shear in the upper troposphere and lower stratosphere appear to become exceedingly complex for practical evaluation by either theoretical or statistical analysis. In the author's opinion, the propagation of lee waves and their behavior leading to turbulence in the lower stratosphere is indeed a subject for which predictability exceeds understanding and curiosity has exceeded revelation.

THE ROLE OF NUMERICAL WAVE SIMULATION

Numerical simulation of atmospheric gravity wave activity can potentially replicate the atmosphere's physical processes for real atmospheric structures in more detail than can typically be observed. Also, in many cases of high altitude turbulence numerical techniques are required for simulation because the layered structure of the winds and temperature lapse rate (stability) becomes too complex for analytical solution methods to be practical or even possible. The relatively small dimensions of high altitude turbulence patches and individual gusts, as well as their association with underlying wave activity, strongly motivate the use of numerical simulation to exploit its ability to describe flow characteristics at much greater resolution than available from upper-air soundings. Moreover, because of the transient nature of wave breaking into turbulence, numerical simulation could potentially augment even in situ aircraft measurements to describe atmospheric flow and to interpret atmospheric structures in regions of strong turbulence.

In the desire to provide better technological services to the public, and to aviation in particular, it is natural to envision the use of numerical simulation in a "black box" style. For such an application, atmospheric structure for a locality of interest would first be obtained from a synoptic- or mesoscale model and would then be used for small-scale wave simulations to produce a refined forecast of high altitude turbulence conditions. This approach to improved forecasting appears logical and straightforward. However, there are salient features that preclude its immediate and successful implementation. Limitations in computational capability, valid comprehensive numerical formulation, and the availability of adequate observations and analyses for simulation input must be overcome to make such small-scale simulations operationally successful on a routine basis. Continuing progress to expand computational capability, to understand atmospheric turbulence and wave behavior, and to improve observational capabilities with advanced technology on the ground and in space is most encouraging.

An example simulation of a thunderstorm-generated gravity wave using a two-dimensional, inviscid, nonlinear, nonhydrostatic numerical model (Refs. 11 and 12) illustrates some attributes needed in the case of gravity wave activity which generates strong atmospheric turbulence. In this case, flow over a thunderstorm cloud line developing in the lower and middle troposphere developed a gravity wave that, in turn, induced turbulence near the jet stream and tropopause level. The modeled streamwise vertical cross sections of potential temperature and horizontal windspeed (Figs. 6 and 7) show the wave pattern for altitudes between 8 and 18 km. At the bottom of the model a solid barrier (darkened) was used to simulate the blocking action of the developing thunderstorm cloud tops in the upper troposphere. Under steady state conditions the potential temperature contours closely parallel the flow streamlines and density contours. Above the tropopause the potential temperature contours are spaced more closely due to the increased static stability in the stratosphere. Regions of dynamic instability (Richardson number less than 0.25) are denoted in figure 6 by the stippled areas. The turbulence encountered by a passenger airliner near the lower stipled

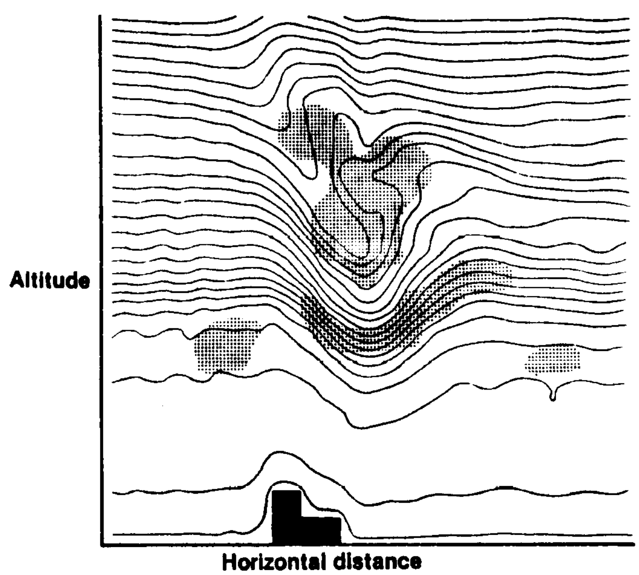


Fig. 6 Potential Temperature Cross Section From a Numerical Gravity Wave Simulation

area in the wave trough contained extreme gust velocities in vortex-like configurations (Ref. 13) that were too small to be resolved by the wave simulation grid spacing used in this case. Airplane respsonse to these gusts threw entree carts and several persons to the ceiling causing injuries and forcing an unscheduled landing. It should also be noted

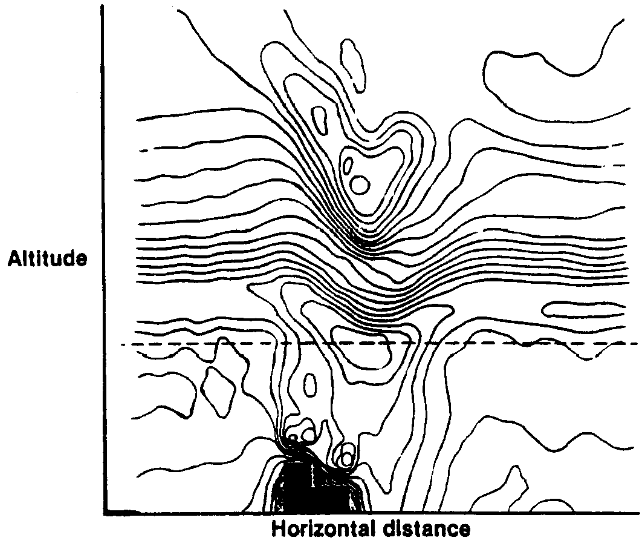


Fig. 7 Horizontal Velocity Cross Section From a Numerical Gravity Wave Simulation

that in the stratosphere the potential temperature contours in the trough steepen and double back over themselves. Here, inside the upper stippled region static stability has vanished (become negative) and the model indicates overturning of the air.

The horizontal velocity field contours (Fig. 7) depict the strong winds accelerating over the cloud barrier with maximum values near the cloud top and also near the tropopause and airplane flight level (dashed line). In the stratosphere the simulated wave pattern tends to roll into an eddy and the closed contours take on negative values where the wind direction reverses. In this zone the overturning flow and vanishing static stability are similar to the behavior in violent mountain wave rotor zones at low altitudes. Another feature of this case is the aspect of nonlinearity associated with the strong winds upstream and over the cloud barrier. Thus for realistic simulation of strong atmospheric events, it is important that the numerical model not be limited to hydrostatic equilibrium and linear behavior (Ref. 14). Examination of the upstream inflow reveals that neither the wind nor the temperature structure exhibits a simple idealized profile amenable to analytical gravity wave motion solutions. Approximation of these fields by analytical forms has achieved some success for lower altitude applications but is not plausible in most cases of interest involving both the troposphere and the stratosphere. Therefore, a numerical model for general use must be capable of realistically using the somewhat arbitrary wind and temperature structures observed in the natural atmosphere.

Even though the desired numerical model capabilities exist and are being improved (Refs. 15-18), their evaluation with respect to observed atmospheric behavior is a very significant future task. Given the possible permutations of forcing inputs and atmospheric profiles, the development of model validation strategy is indeed challenging. The potential complexity is especially intriguing in view of the tendency for dynamic perturbations in the natural atmosphere to cycle or pulse at relatively short intervals. Because of these realities the role of numerical gravity wave simulation is perceived to be first a diagnostic tool for atmospheric research; second, a subject of experimental development to determine the necessary model attributes and the atmospheric situations in which specific attributes are needed; and finally, an operational forecasting tool at regional or specialized forecast centers. In this development cycle two aspects are paramount for the meteorologist as an atmospheric observer and as a forecaster of turbulence at supersonic cruise altitudes in the stratosphere. First, to simulate motions in the lower stratosphere, what degree of detail is important in the lower troposphere structure and in forcing features such as terrain, localized wind flow, and stability profiles? Second, what are the effects of input data resolution, model gridpoint density, and numerical smoothing in the upper troposphere and stratosphere? To address these aspects and to validate numerical model developments, the aircraft turbulence encounters used for the meteorological studies described in the previous section should provide several pertinent case studies for comparison of simulation with observed atmospheric turbulence and wave behavior. To augment the perspective provided by aircraft data additional comparison case studies should be based on observations from ground-based systems such as MST doppler radar at Poker Flat, Alaska, and Platteville, Colorado, which sense refractivity turbulence structure (Ref. 19), as well as from satellite observations.

Two additional observed meteorological aspects also motivate the study of gravity wave behavior associated with turbulence at SCA cruise altitudes. According to classical gravity wave theory an effect of upward propagating wave motion is to decelerate the downstream wind velocity component. When a critical altitude is reached at which the windspeed equals the wave speed (that is, windspeed equals zero for a standing wave) the remaining wave energy would decelerate the flow, conceivably through a concentrated turbulence process. Above this critical layer altitude there would be no effects of the lower altitude wave motion. Another result of analysis is the indication of an inherent tendency for wave oscillations to amplify with altitude in a decreasing wind profile (Ref. 14). For some conditions, this amplification may lead to destabilization and overturning at altitudes significantly below the critical level. With respect to these analytical considerations one meteorological feature observed to delineate between turbulence and no turbulence is the vertical gradient of kinetic energy. The value of this gradient has been derived as the product of windspeed and vertical wind shear measurements obtained directly from rawinsonde data. It has also been derived as the product of windspeed and horizontal temperature gradient (thermal wind) obtained from analysis of mandatory level upper-air charts. The threshold value of the kinetic energy gradient associated with high altitude turbulence decreases markedly with altitude. For example, at 18 and 20 km the threshold values are approximately 65 percent and 25 percent, respectively, of the threshold value at 16-km altitude. Another relevant meteorological observation is the occurrence of supergeostrophic windspeeds at the 150-, 100- and 70-mb pressure levels (14-, 16-, and 18-km altitudes) in some cases of widespread high altitude turbulence over the western United States. It is implied that the upward momentum flux from the strong jet stream winds below the 150-mb level (14-km altitude) significantly exceeds the wave drag deceleration effect in these cases. These observations suggest that vertically propagating wave motion can significantly amplify in the weaker flow above the level of the maximum wind and cause much turbulence at altitudes appreciably below the critical level.

CONCLUDING REMARKS

This paper has described the characteristics of turbulence encountered by aircraft at supersonic cruise altitudes. Turbulence intensity exhibits predictable relationships with the strength of atmospheric features such as windspeed, temperature structure, and numerous derived parameters. The data show that lower altitude gravity wave motion is involved in a major portion of high altitude turbulence encounters. Turbulence patch thicknesses of less than 1 km suggest that turbulence generation occurs in relatively shallow layers of atmospheric structure that are responding to larger scale wave excitation. A promising avenue to improved understanding of atmospheric turbulence and wave behavior at SCA cruise altitudes and above is continued progress in numerical gravity wave modeling. Comparison of observation and numerical model results will aid in this development. It is suggested that the most efficient avenue to progress will include a team effort with expertise in aircraft measurements, atmospheric observations, mesoscale analysis, and applied forecasting, as well as skills in gravity wave model formulation and theoretical atmospheric dynamics. A better understanding of the interaction between wave behavior and turbulence processes in the lower stratosphere would not only benefit SCA operations but would also provide more knowledgeable estimates of transient atmospheric properties for the design and flight simulation of future advanced vehicles traversing altitudes of 50 to 80 km in the upper stratosphere and mesosphere.

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16. Abstract

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